Transition Edge Sensor Using Dilute AlMn Alloys

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We have fabricated a transition-edge sensor (TES) using Mn to suppress the superconducting critical temperature (T_c) of Al from ~1 K to ~100 mK. The resulting detector exhibits in-band noise consistent with theory, with a noise-equivalent power of 7.5 x 10^{-18} W/√Hz. The addition of Mn impurities did not significantly increase the heat capacity of the TES. In addition, the detector is surprisingly insensitive to applied magnetic fields. The use of AlMn alloy films in arrays of TES detectors has advantages in simplicity of fabrication and device robustness when compared to traditional bilayer fabrication techniques.

I. Introduction

In this paper, we report the results from a superconducting transition-edge sensor (TES) fabricated using manganese impurities to reduce the T_c of an aluminum film from ~1 K to ~100mK. We have found noise close to theoretical predictions, low noise-equivalent power (NEP), and a low sensitivity of the sensor to magnetic fields. These features, in addition to the ease of fabrication, make Al-Mn an attractive candidate for use in TES bolometers and microcalorimeters.

TES detectors have become an important detector technology for sensitive photon detection in submillimeter, optical, and X-ray regimes [1-3]. These detectors offer excellent sensitivity, despite having some unexplained noise. An important reason for their popularity has been a clear path towards large-format arrays. TES detectors can be multiplexed cryogenically [4], and TES arrays with ~ 10,000 pixels are presently being fabricated [3]. Because of this success, there is ongoing interest in improving the noise performance, robustness, and ease of fabrication of TES detectors.

An important parameter of TES sensors is the superconducting transition temperature, T_c. Because T_c strongly affects heat capacity, thermal conductivity, and thermal noise of the sensor, careful control of T_c is necessary to optimize a sensor for a given application and cryogenic platform. Since the T_cs of elemental superconductors are not usually optimal, the T_c is often engineered by fabricating bilayers of superconducting and normal metals. The T_c of the superconducting metal is suppressed by the presence of the normal metal through the proximity effect [5]. Controlling the T_c of a bilayer is technically challenging, as the T_c is a sensitive function of the properties of both layers, as well as the interface transparency.

Another technique is to use doping with ferromagnetic impurities to adjust the T_c of an elemental superconductor. The impurity method is simpler and potentially more reproducible, as only one homogeneous layer of superconducting material is used in the TES. The leads can be made out of the non-doped elemental superconductor, eliminating the risk of chemical interactions between different materials during processing. In both proximity bilayers and ferromagnetic doping, the dominant operative effect depressing T_c is traditional pair-breaking, originally elucidated by Abrikosov and Gor'kov (AG) [6-8], lately modified to include antiferromagnetic coupling effects, the latter of which reduce pair breaking and raise T_c [9].

While the T_c of tungsten has been adjusted for use in a TES by the implantation of ions of ferromagnetic species including iron and cobalt in the ~100 ppm range [9], it is not ideal for many TES applications. Tungsten has a high resistivity and its T_c is strongly dependent on film morphology, making it difficult to fabricate. Aluminum is an attractive alternative for TES applications due to its robustness, lower resistivity and ease of deposition.

For many applications, it is desirable to reduce the T_c of Al to ~ 100 mK. However, as confirmed with ion implantation, doping with ferromagnetic metals does not produce a substantial decrease in the T_c of aluminum, even at relatively high concentrations [10]. Instead, we have developed a TES using Al doped with Mn. While Mn can drive the T_c of Al to below 50 mK, this occurs for Mn concentrations in the ~ 3000 ppm regime, suggesting that AG pair breaking is not the principle agent, and rather that T_c

suppression in Al-Mn alloys is due to pair scattering from resonant impurity sites in the context of the Friedel-Anderson model [11], as quantified by the Kaiser theory [12]. This conjecture is substantially reinforced by tunneling measurements in AlMn/I/AlMn tunnel junctions [13] that show BCS-like tunneling characteristics with conductance characteristics exhibiting the complete absence of gap smearing from paramagnetic pair breaking.

II: Fabrication

An Al-Mn alloy (99.7%/0.3%) sputter target is used in a co-sputter system with a pure aluminum target. By varying the deposition rate of each target as they are sputtered onto a rotating silicon wafer, Al films with different concentrations of Mn are produced. Al-Mn films have been fabricated with T_c of less than 58 mK up to the bulk T_c of the aluminum, ~1 K [Fig. 1a]. At a T_c of ~100 mK, the residual resistivity ratio of the films is ~1.5. The resistivity of these films at 100 mK (~2.4 μΩ cm) is fairly high, making it necessary to use thick films for applications requiring low sheet resistance.

A 400 nm thick film of Al-Mn was patterned into a 400 μm square with an aluminum wet etch. Pure aluminum leads were evaporated through a photoresist liftoff stencil. The TES was deposited on a silicon wafer with a 350 nm coating of Si_3N_4. Silicon was removed from beneath the TES by a deep reactive-ion etch process, providing a free-standing nitride membrane for the necessary thermal isolation. Fig. 1b shows a photomicrograph of a completed detector.

III. Detector Test Results.

The detector was cooled in an adiabatic demagnetization refrigerator. The T_c of the detector is 112 mK, with a normal resistance R_N = 72.4 mΩ. The detector has a broad transition, as quantified by the unitless measure of transition steepness, $\alpha = (T/R)(dR/dT) \approx 31$. Fig. 2a shows the noise spectrum of the device, biased at 0.25 R_N and measured with a SQUID current amplifier. Superimposed is a noise model based on the measured properties of the detector [1]. There are no free parameters in this model, and it is a good match in the low frequency, phonon noise dominated part of the spectrum. At higher frequencies, where Johnson noise dominates, the measured excess noise for the Al-Mn TES is ≈ 50 %. This is substantially better noise performance than is typical for TES sensors, where excess noise of ≈ 200 % is often exhibited at these frequencies. The measured in-band noise-equivalent power is 7.5 x 10^{-18} W/√Hz, consistent with theoretical expectations.

The detector was exposed to 5.9 keV Fe^{55} X-rays. Because no absorber was used, the detector had a low cross-section to X-rays, making it difficult to collect a spectrum. However, the X-rays did produce pulses, as shown in Fig. 2b. Comparing the noise of the device to the measured X-ray pulse heights predicts an energy resolution of ~2 eV, assuming no further sources of noise (e.g. position dependence) come into play. It is impossible, however, to determine the energy resolution of this system until it has been tested with an absorber. We calculate heat capacity C=2.6 60.3 pJ/K from the measured time constant, thermal conductivity, and α. This value is ~10 % higher than the calculated heat capacity of a pure Al film, indicating that the presence of Mn has not significantly increased the Al heat capacity.

The Al-Mn TES was extremely insensitive to magnetic field. A magnetic field was applied perpendicularly to the surface of the detector. The detector's resistance vs. bias voltage was measured with zero applied field and again for an applied field of 2.21 x 10^{-5} T. The same was done for a Mo-Cu bilayer TES, with an applied field of 1.76 x 10^{-5} T. Fig. 3 shows a plot of change in resistance vs. the resistance of the device at bias (normalized to R_N, the normal resistance of the TES) for both devices. At a bias voltage of 0.25 R_N, the Mo-Cu resistance changes by 175 %, while the operating resistance of the Al-Mn TES changes by 6.8 %. The noise performance of the Al-Mn device was unchanged before and after the field was applied.

IV. Analysis

We have successfully tested an Al-Mn TES. The fabrication of Al-Mn TES detectors is simpler than that of bilayer detectors. However, there are two properties that must be considered when using Al-Mn in a TES detector. The resistivity of Al-Mn films is higher than that of Mo-Cu sensors, so thick films may be required for good thermalization and low position dependence in X-ray microcalorimeters. The use of an absorber incorporating a metallic layer may eliminate thermalization problems. It may also be possible to produce a bilayer of Al-Mn and pure Al to improve sheet resistance. Further, because the α of the Al-Mn TES is low compared to that of Mo-Cu bilayers, a lower heat capacity will be needed for high count rate X-ray microcalorimeter applications.

Its low excess noise also makes the Al-Mn TES an interesting candidate for bolometric applications. It is unclear whether the low excess noise is caused by the magnetic impurities, or by the detector's low α. Previous measurements [14] indicate that low-α detectors have low excess noise, and this measurement seems to agree with the results from low-α Mo-Cu detectors.

The magnetic field sensitivity of TES detectors is the cause of some concern in instrument design, since they must be carefully shielded from fields produced by both the instrument and the observing environment. A small magnetic field gradient across a TES array could produce different bias resistance values within the array, producing inconsistent results from one pixel to the next. The low magnetic field sensitivity of this doped system may result in arrays that are much more robust in instruments.

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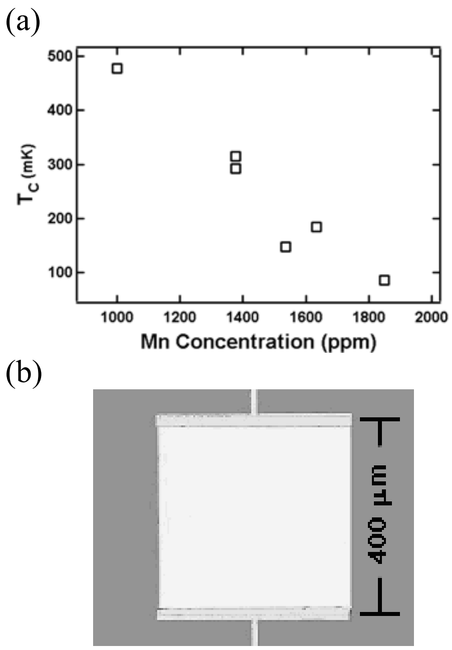

Fig. 1: (a) Dependence of T_c in Al on Mn concentration. (b) Optical micrograph of an Al-Mn TES.

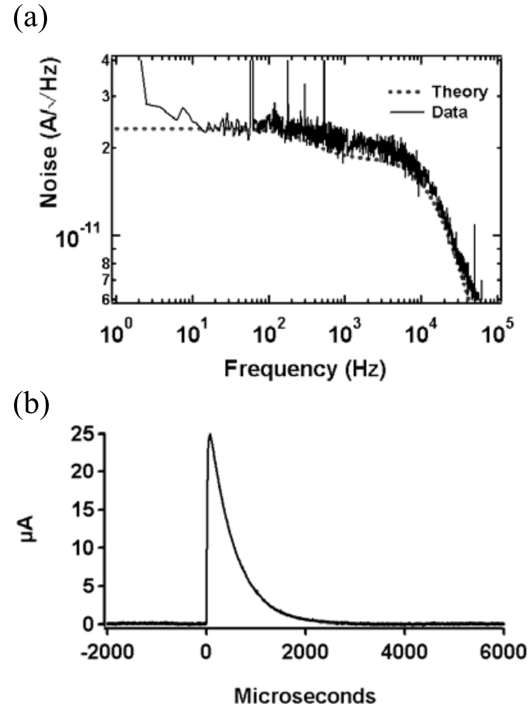

Fig. 2: (a) Noise of the Al-Mn TES detector. (b) Fe^{55} X-ray pulse in the detector.

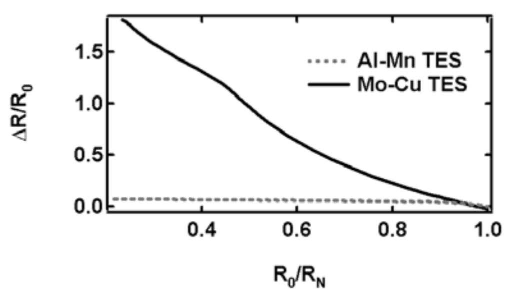

Fig. 3: The ratio of the change in TES resistance with field to resistance without ($\Delta R/R_0$) vs. the resistance of the device at bias (normalized to R_N, the normal state resistance).